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NASA TN D-1337

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TECHNICAL NOTE

D-1337

A TUNNEL-DIODE COUNTER FOR SATELLITE APPLICATIONS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON June 1962

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SUMMARY

Binary counters employing tunnel diodes as the bistable device have been developed for operation at much higher counting rates (up to 5 Mc) than other counters with comparable power dissipation and number of components. They operate reliably within wide supply-voltage tolerances and over a temperature range of -50° to +100°C which makes them suitable for satellite operations. They are also simple in construction, and standard 10-percent-tolerance components may be used in the circuits.

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INTRODUCTION

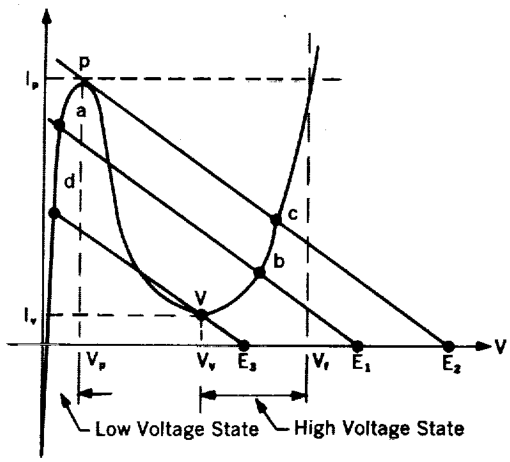
The use of high-speed binary counters in satellite applications places ever-increasing demands for simplified construction, low power requirements, and high reliability. Tunnel diodes can, with suitable load resistances, be made to operate as bistable (or memory) devices. Moreover, if transistor coupling is used between stages, reliable operation can be obtained within a wide variation in supply voltage and in a temperature range suitable for satellite applications. Because of these characteristics, tunnel diodes can be used to construct binary counters with the advantages of simplicity, low power consumption, high speed, and excellent reliability.

This report describes both single and multistage binary counters made with tunnel diodes. Experimental data on these circuits and an analysis of the transistor interstage coupling are given in the Appendixes.

TUNNEL-DIODE CHARACTERISTICS

The tunnel diode is a two-terminal semiconductor device that exhibits a bistable operating characteristic in the forward-current region. The tunnel diode will operate as a bistable (or memory) device if and only if the load-line is so chosen that it intersects the E-I characteristic curve in both the positive resistance regions. Such a load-line is shown by the line ab in Figure 1. If the supply voltage is increased above the value E_2 (Figure 1), the load-line will be shifted above the point p and will intersect the E-I curve in only one of the positive-resistance regions. In this case, the only stable operating point will be in the high-voltage state. If the supply voltage is decreased below the value E_3, the only stable operating point will be in the low-voltage state.

Figure 2 shows a simple tunnel-diode bistable circuit. With S1 and S2 both open (R_s and E are chosen to form load-line ab in Figure 1) the diode can operate at point a or point b. If S1 is momentarily closed and then opened, the diode will be placed in the high-voltage state, point b. If S2 is momentarily closed and then opened, the diode will



I_p = peak current
I_v = valley current
V_p = value of the voltage at peak value
V_v = value of the voltage at the valley

Figure 1 —Tunnel-diode voltage-current (E-I) characteristics for bistable operation

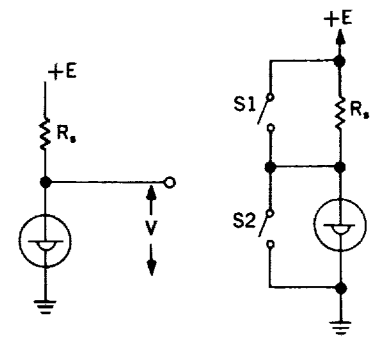


Figure 2—A simple tunnel-diode bistable circuit

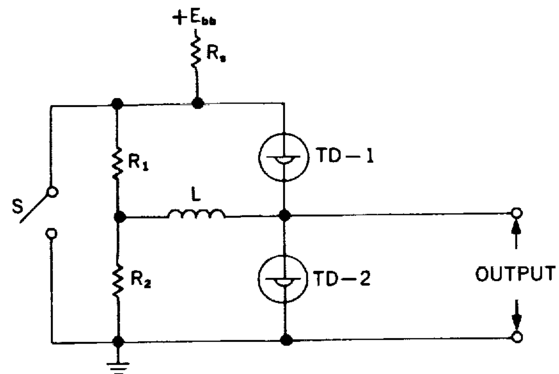
be placed in the low-voltage state, point a. In either state, the operating point remains stable until the current through the diode is appropriately changed.

THE TUNNEL-DIODE FLIP-FLOP

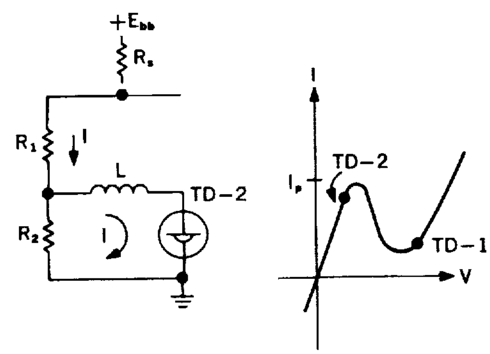
A Chow* tunnel-diode flip-flop is shown in Figure 3a. The supply voltage E_{bb} and resistors R_s, R1, and R2 are selected so that only one or the other of the two tunnel diodes can be in the high-voltage state under steady-state conditions. The bistable operation of the circuit in Figure 3a can be explained by assuming the diode TD-2 to be initially in the low-voltage state; under this condition the steady-state current flow through the circuit is as shown in Figure 3b. (For the purpose of explanation, the small amount of current that flows through the diode that is in the high-voltage state, TD-1 in this case, can be neglected satisfactorily.)

If switch S (Figure 3a) is momentarily closed, the steady-state current shown in Figure 3b is interrupted and the circuit currents are altered. The two tunnel diodes are constrained to have a net voltage of zero across the pair because of the short circuit caused by switch S. To meet this constraint and that imposed by the electrical inertia of the inductor, current will continue to flow in the same direction in TD-2 and a reverse current will flow in TD-1. These circuit-currents and the resulting tunnel-diode operating points are indicated in Figure 3c. If switch S is opened while the stored inductor

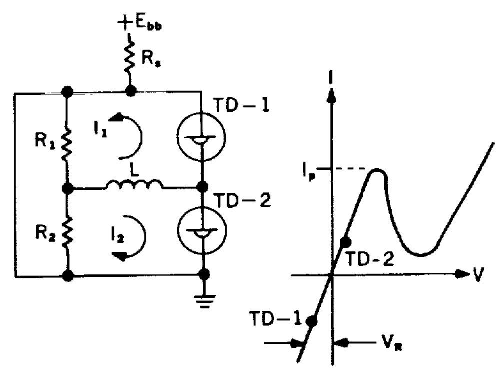
*Chow, W. F., "Tunnel-Diode Digital Circuitry." IRE Trans. on Electronic Computer EC-9(3): 295-301, September 1960.



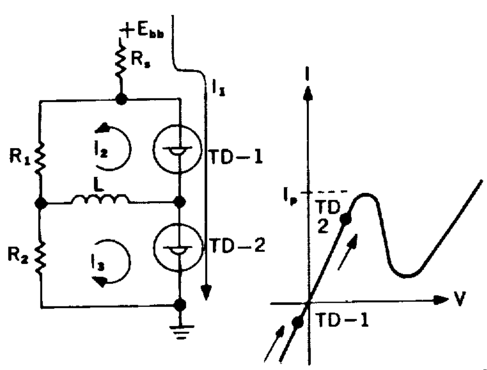
a. Tunnel-diode flip-flop circuit.



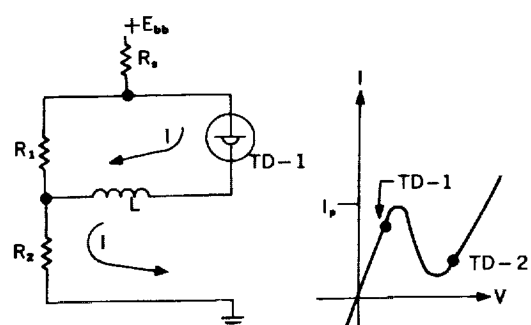
b. Diode TD — 2 in the low voltage state and switch S open.



c. Circuit currents immediately after closing switch S.



d. Circuit currents immediately after reopening switch S.



e. Steady-state conditions after switch S is opened.

Figure 3—Tunnel-diode flip-flop analysis

current is still flowing, the current from the power source E_{BB} will algebraically add to the currents from the inductor; this will cause the operating points of both diodes to shift in the directions of the arrows shown in Figure 3d. When the current through TD-2 reaches the I_p level, TD-2 will switch to the high-voltage state and TD-1 will then go to the low-voltage state. The new operating points of TD-1 and TD-2 are shown in Figure 3e. Comparison of Figures 3b and 3e shows the reversed conditions of the two diodes after one-half of a cycle. If switch S is again momentarily closed, the reverse action with respect to TD-1 and TD-2 will take place, and the circuit will return to the original state, that shown in Figure 3b, thus completing one cycle.

The shorting time of switch S must be less than the L/R time constant of the circuit of Figure 3a. If this condition is not met and the inductor current decays below a critical level, the steady-state condition will be unpredictable after the switch is opened.*

In general, any disturbance that momentarily places both diodes in the same voltage state will cause the circuit of Figure 3a to switch states.†

Figure 4 shows two successive Chow tunnel-diode flip-flops with capacitive coupling. This circuit was operated at the Goddard Space Flight Center as a counter chain with an input in the megacycle range. It was observed that the use of capacitive coupling between successive stages of tunnel-diode flip-flops presents the disadvantage of limited tolerance to supply-voltage changes which makes the circuit of Figure 4 unsuitable for satellite applications. (Experimental data taken from the circuit of Figure 4 are given in Appendix A.) However, the combination of the simplicity and otherwise reliable operation of the basic tunnel-diode flip-flop circuit prompted the design of a transistor interstage coupling circuit that would overcome this limitation.

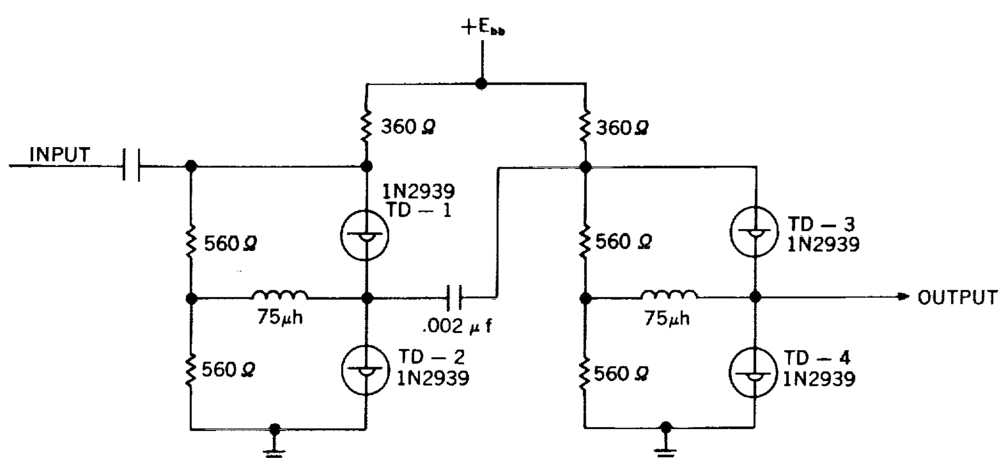


Figure 4 — Two-stage Chow tunnel-diode flip-flop with capacitive coupling between stages

*For a complete analysis of the effect of L and R, see Chow, op. cit.

†General Electric Co., Semiconductor Products Dept., "Tunnel Diode Manual," 1st Edition, Syracuse, N.Y., 1961.

TRANSISTOR COUPLING

Figure 5 shows the circuit of Figure 4 modified to employ transistor coupling between successive stages. A silicon instead of a germanium transistor is used because the temperature characteristic of the silicon transistor is more compatible with that of the germanium tunnel diode.

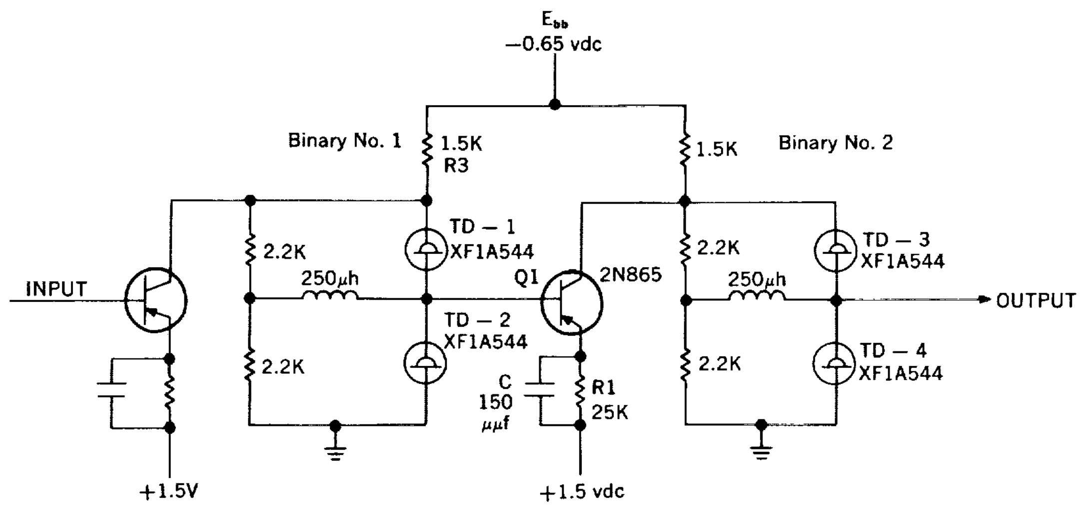


Figure 5 — Two-stage Chow tunnel-diode flip-flop with transistor interstage coupling

The silicon transistor emitter-base offset voltage posed a design problem because at low temperature the offset voltage becomes greater than the amplitude of the signal that is to be coupled. The problem was overcome by returning the emitter to a +1.5-v bias supply and shunting the emitter resistor with a 150-μμf capacitor. This bias arrangement allows a quiescent dc collector current of about 30μa to flow in the transistor. The effect of the small collector current is negligible at Binary No. 2, but it allows the transistor to operate as an emitter-follower when no transient signal is present at the base. When a negative switching transient from Binary No. 1 appears at the base, the base voltage drops immediately, but the capacitor across the emitter-resistor prevents any instantaneous change in the emitter dc level. Under this condition, the base current increases appreciably, on the order of 80μa, and drives the transistor to saturation. When the transistor saturates, it acts as a momentary short circuit across Binary No. 2, which then switches state in the same manner as the circuit of Figure 3a. The RC time constant of the resistor and capacitor in the emitter circuit is chosen to keep the transistor in saturation for 200 nanoseconds* which is compatible with the L/R time constant of the binary stage. (A more complete analysis of the transistor coupling circuit is given in Appendix B.) It should be noted here that an NPN transistor may be substituted for the PNP 2N865 if the tunnel-diode connections are reversed and all voltage polarities are reversed.

*One nanosecond = 10^{-9} second.

THE XF1A544 TUNNEL DIODE

The tunnel diode used in the circuit of Figure 5 is a General Electric Company type XF1A544 (germanium). This diode was specially manufactured to specifications (a peak current I_p of 0.25 ma) that evolved from studies of tunnel-diode counters for this application. The lowest value of I_p for tunnel diodes listed in published catalogs was 1.0 ma. It was learned, however, that the peak current could be reduced to as low as 0.25 ma, saving power without changing the essential characteristics for flip-flop application.

The 0.25-ma diode was temperature tested and the results, compared with temperature test data on a standard 1-ma 1N2939 tunnel diode are shown in Figure 6. The low temperature for the test was limited by the available testing apparatus; the high temperature was held to 100°C because of manufacturer's recommendations. The XF1A544 diode shows a greater percentage change in peak current than does the 1N2939. In the 1N2939, the change in peak current I_p from -50° to 100°C is about 5 percent; the XF1A544 peak current changes nearly 30 percent over the same temperature range.

A FOUR-STAGE XF1A544 TUNNEL-DIODE BINARY COUNTER

Figure 7 is a schematic diagram of a four-stage tunnel-diode binary counter that uses the silicon transistor coupling circuit and the XF1A544 tunnel diode. This counter was operated with input count rates from 0 to 2.5 Mc; the performance over this counting range was stable and reliable.

The allowable variation in supply voltage for reliable operation varies with the ambient temperature of the tunnel diodes. Figure 8 shows the effect of temperature variation; the shaded region indicates the tolerable supply voltage operating range. If 0.65 v is taken as the nominal supply voltage, Figure 8 shows an allowable tolerance of ±23 percent at an ambient temperature of 25°C. At -50°C, the tolerance is +30 percent and -20 percent. At 100°C the supply voltage tolerance for stable operation is +10 percent and -23 percent. The negative slope of the high voltage limit is due to the change in the tunnel diode E-I characteristic with temperature; at high temperature less voltage is required to maintain the diode in the high-voltage state. As was stated previously, the supply voltage must be maintained at a sufficiently low value so that only one or the other diode can be in the high voltage state; therefore, the supply voltage has to be decreased at the increased temperature to maintain reliable operation.

Loading the binaries also reduces the tolerable range of the voltage supply. Tolerable supply voltage (E_{BB}) ranges for several different loads at an ambient temperature of 23°C and at a counting rate of 2.5 Mc are given in Table 1.

At a nominal E_{bb} value of -0.65 v, one XF1A544 binary stage dissipates 130μw of power. The coupling circuit dissipates 70μw (at 1.5 v bias); the total power per stage is 200μw.

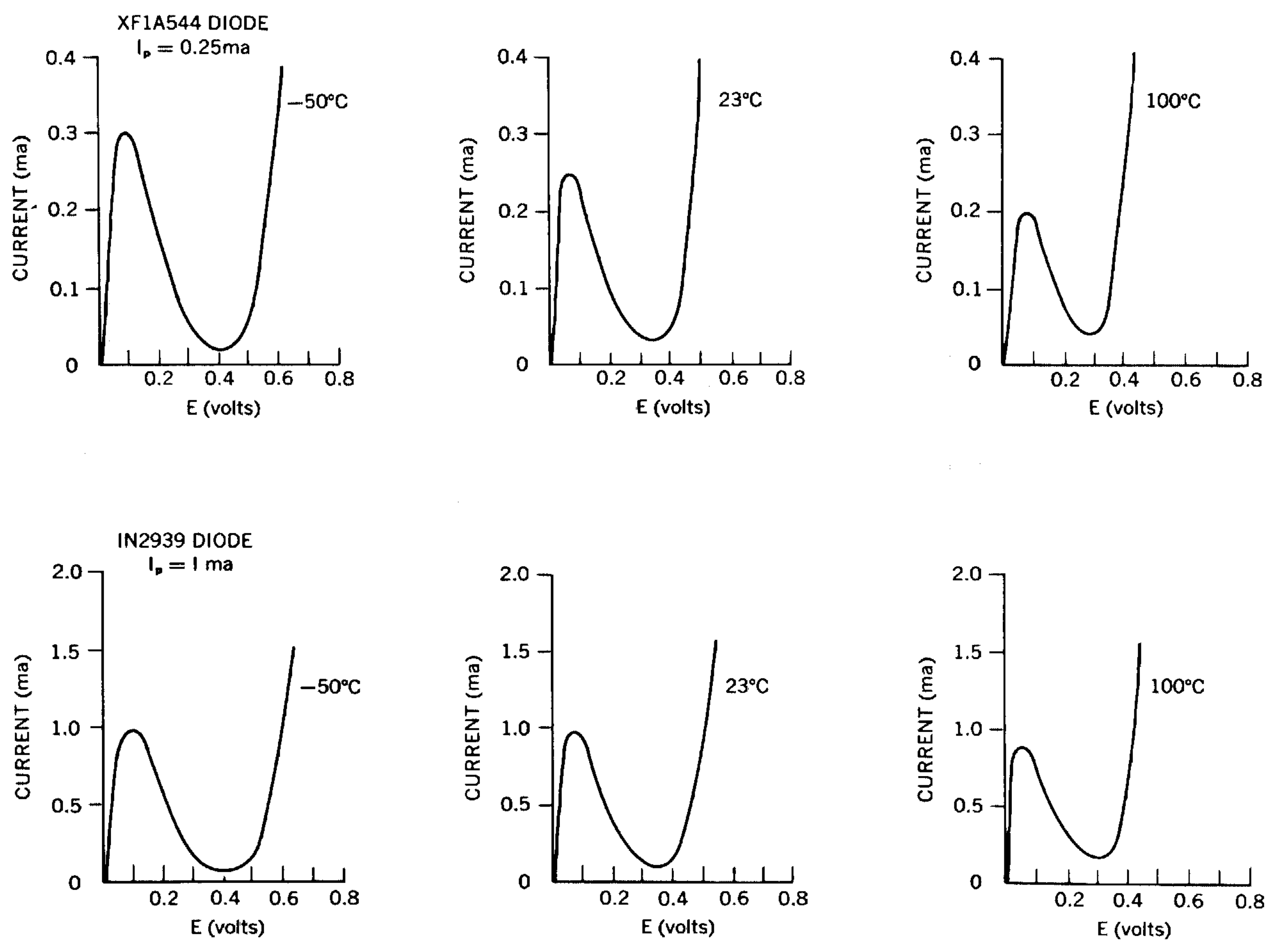
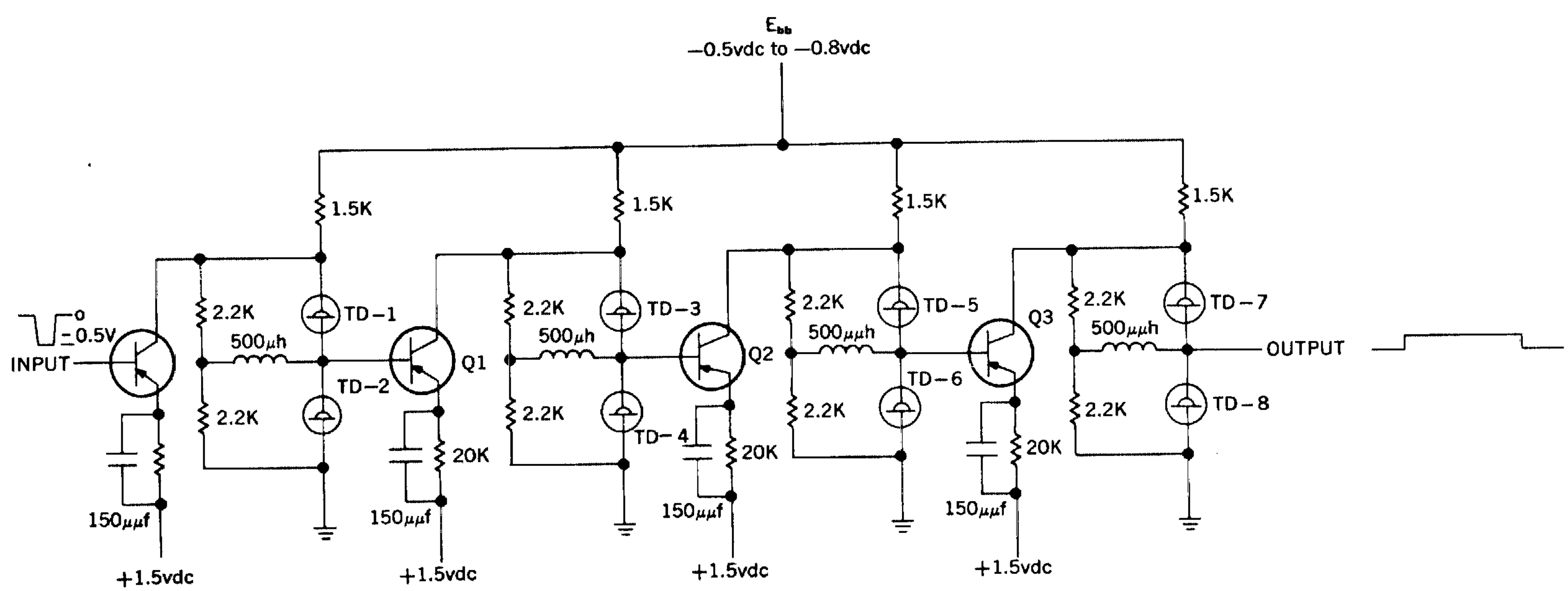


Figure 6—Comparison of the temperature characteristics of the 1N2939 and XF1A544 tunnel diodes



NOTE:
TD − 1 through TD − 8
are GE XF1A544 diodes

Figure 7—A four-stage tunnel-diode binary counter using the silicon transistor coupling circuit

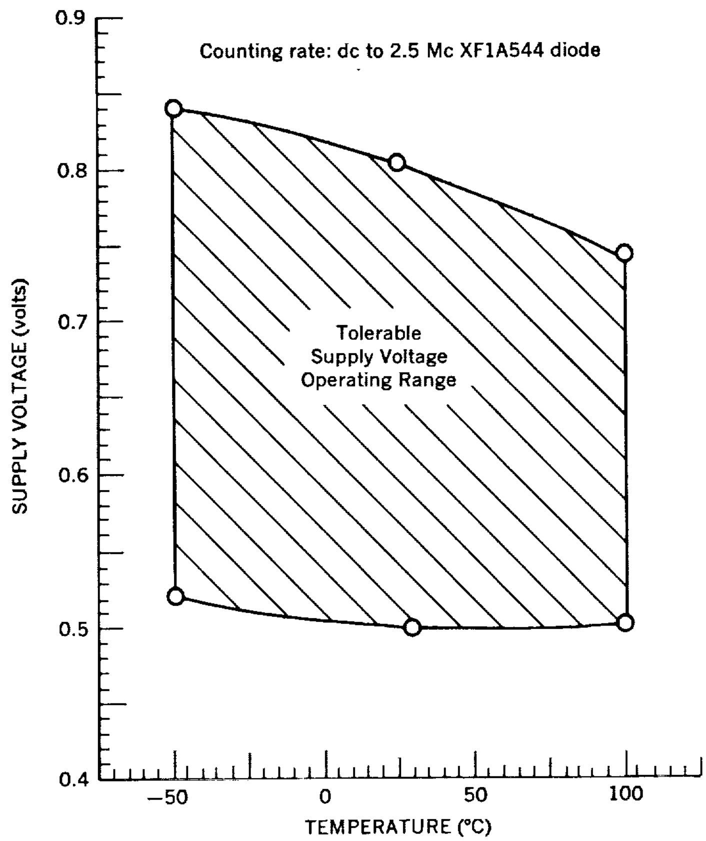


Figure 8—Tolerable supply voltage operating range

Table 1

Tolerable Supply Voltage Ranges for the Four-bit Binary Counter for Several Different Loads

Load Resistance (ohms)	Tolerable Supply Voltage Range at 23°C (volts)
Open circuit	0.50 to 0.80
10K	0.50 to 0.77
5K	0.50 to 0.73
3K	0.55 to 0.64

A 1N2939 TUNNEL-DIODE BINARY COUNTER

Before experimenting with the XF1A544 diode, extensive investigation of the tunnel-diode binary was carried out with 1N2939 tunnel diodes, which are quite suitable for satellite applications. The performance of the 1N2939 diode equals that of the XF1A544 except in power dissipation. Figure 9 shows a typical stage of an eighteen-stage binary counter in which the 1N2939 diode was used. With a peak current I_p of 1 ma, the power consumption for this stage is 455μw for the binary and 70μw for the coupling stage; the total power per stage is 525μw. The supply voltage tolerances and temperature ranges for reliable counting operation were as good or better with the 1N2939 as with the XF1A544; the 1N2939 counter has been operated with an input rate up to 5.0 Mc.

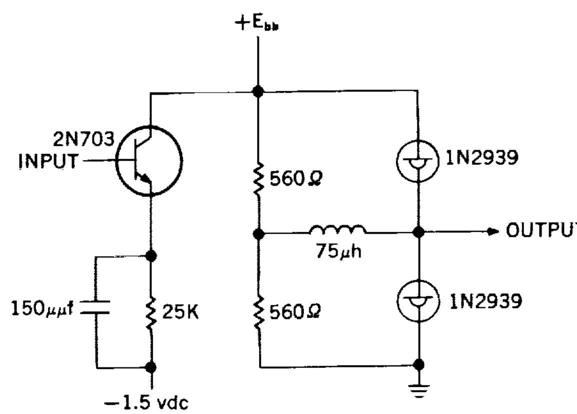


Figure 9—Typical stage of an eighteen-stage binary counter in which the 1N2939 tunnel diode was used

OUTPUT CIRCUITS

Since the output voltage directly obtainable from a tunnel-diode binary stage is not suitable for most satellite applications, the output circuit of Figure 10 was designed to develop a useable output. The collector of the output transistor is at -5.0v when the binary is "on" and at ground when the binary is "off". The output circuit constitutes a high impedance load to the binary stage, which is a necessary condition for good supply voltage tolerance. When TD-2 of Figure 10 is in the low-voltage state, the anode voltage of the 1N252 diode is on the order of 50 mv. The cathode of the 1N252 diode is returned to the -5.0-v collector supply through resistor R1. Under this condition, a current of approximately 9μa flows through the series path of TD-2, the 1N252 diode, and R_1. The resultant voltage drop across TD-2 and the 1N252 diode is slightly less than the base-emitter voltage necessary to cause

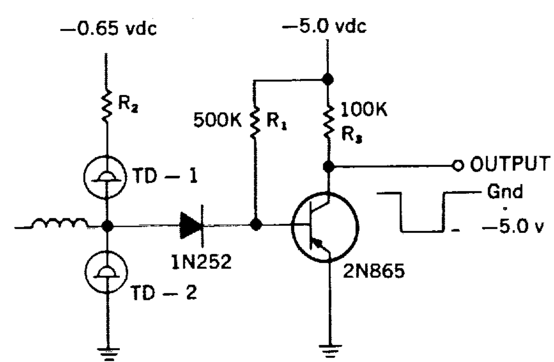


Figure 10—Output circuit used with tunnel-diode binary circuits

the transistor to conduct; therefore, the transistor is at cutoff, and the collector is at -5.0 v (with no load). When TD-2 switches to the high-voltage state, the anode of the 1N252 diode goes to approximately -0.5 volts. The voltage drop across the 1N252 diode then places the base of the transistor at about -1 v; this is enough to saturate the transistor and drive the collector nearly to ground potential. Thus, the output voltage switches from -5.0 v to ground.

Temperature compensation for the variation in the emitter-base offset voltage of the transistor is achieved from the 1N252 diode, which has nearly the same offset-voltage versus temperature characteristic. This circuit has operated satisfactorily from -50° to 100°C.

A three-stage binary counter employing the output circuit of Figure 10 has been used satisfactorily with encoder gating circuitry to control the frequency of an eight-level digital oscillator.

CONCLUSIONS

The tunnel-diode binary counter operates at much higher counting rates than other counters with comparable power dissipation and number of components. The operating temperature range of the tunnel diode is suitable for satellite applications without temperature compensation in the binary circuit. The reliability of the tunnel diodes appears to be excellent; approximately 60 units have been used in various circuits over a six month period, and no failures have been observed during operation. The tolerable variation in supply voltage permits the use of an unregulated power source for these counters. The tunnel diodes themselves do not require matching or selection, and standard 10 percent tolerance components may be used in the circuitry.

Appendix A

Experimental Data on Tunnel-Diode Flip-Flops

The data in Table A1 were taken from circuits having the configuration of Figure 4, employing 1N2939 (1-ma) tunnel diodes. No attempt was made to match the tunnel-diode characteristics:

Table A1

Experimentally Determined Supply Voltage Ranges for Reliable Operation of Tunnel-Diode Flip-Flops with 1, 2, and 3 Stages

Number of Stages	Tolerable Supply Voltage Range at 23°C	
	Low Supply Voltage	High Supply Voltage
2	0.52 to 0.63	0.7 to 0.84
3	0.50 to 0.56	0.73 to 0.82
4	erratic operation	0.76 to 0.80

The two separate supply voltage ranges for normal operation may be explained by noting that tunnel-diode flip-flops can be switched by applying to the circuit a pulse of the correct polarity and of sufficient magnitude to set both tunnel diodes momentarily into the same state. At high supply voltages, a positive pulse will momentarily place both diodes into the high-voltage state; at low supply voltages, a negative pulse will momentarily place both diodes into the low voltage state.

For supply voltages in between the ranges listed in Table A1, pulses of either polarity will switch the diode states; since the capacitor will pass pulses of either polarity, the flip-flop will switch on both polarities and the circuit will not act as a binary.

Appendix B

Analysis of Transistor Coupling Circuit

The transistor coupling circuit Q_1 shown in Figure 5 is analyzed as follows: If TD-2 is in the low-voltage state, then the emitter current I_e is approximately given by the formula

$$I_E \approx \frac{E_{EE} - E_{EB} \text{ offset}}{R_1 + h_{ib}}$$

$$\approx 37\mu a,$$

where $E_{EE} = -1.5$ v is the emitter supply voltage; E_{EB} offset = -0.5 v is the emitter-to-base offset voltage; R_1 = 25K; and h_{ib} = 2.0K is the base-to-emitter resistance at the voltage used. The base current I_b is

$$I_b = \frac{I_e}{h_{fe}}$$

$$= 3.7\mu a,$$

where $h_{fe} = 10$ is the current gain of the transistor. The collector current I_c is then

$$I_c = I_e - I_b$$

$$= 33\mu a.$$

With a 0.5 volt-transient applied to the base of Q_1 through R_3, the increase in I_b is

$$\Delta I_b = \frac{-\Delta E_{EB}}{R_3 + R_i}$$

$$= 77\mu a,$$

where $\Delta E_{EB} = 0.5$ v is the increase in E_{EB}, R_3 = 1.5K, and R_i = 5K is the input resistance of the transistor as a grounded emitter. An increase of 77 microamperes in the base current will effectively saturate Q_1.

NASA-Langley, 1962 G-215

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National Aeronautics and Space Administration.
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(NASA TECHNICAL NOTE D-1337)

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